

Constraints on the primordial power spectrum of small scales using the neutrino signals from the dark matter decay

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Many inflation theories predict that the primordial power spectrum is scale invariant. The amplitude of the power spectrum can be constrained by different observations such as the cosmic microwave background (CMB), Lyman- α , large-scale structures and primordial black holes (PBHs). Although the constraints from the CMB are robust, the corresponding scales are very large ($10^{-4} < k < 1\text{Mpc}^{-1}$). For small scales ($k > 1\text{Mpc}^{-1}$), the research on the PBHs provides much weaker limits. Recently, ultracompact dark matter minihalos (UCMHs) was proposed and it was found that they could be used to constraint the small-scale primordial power spectrum. The limits obtained by the research on the UCMHs are much better than that of PBHs. Most of previous works focus on the dark matter annihilation within the UCMHs, but if the dark matter particles do not annihilate the decay is another important issue. In previous work,¹ we investigated the gamma-ray flux from the UCMHs due to the dark matter decay. In addition to these flux, the neutrinos are usually produced going with the gamma-ray photons especially for the lepton channels. In this work, we studied the neutrino flux from the UCMHs due to the dark matter decay. Finally, we got the constraints on the amplitude of primordial power spectrum of small scales.

Keywords: dark matter; neutrino; primordial power spectrum

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1. Introduction

It is well known that the cosmic structures are originated from the primordial density perturbations which are produced during the inflation. Most of inflation theories predict that the primordial power spectrum (PPS) of density perturbations is scale invariant.² The PPS ($\mathcal{P}_{\mathcal{R}}(k)$)^a can be constrained by some observations. At present, the limits are mainly from the observations on the cosmic microwave background (CMB), Large-scale structures, Lyman- α forest and microlensing effect.⁴⁻⁷ But these constraints focus on large scales, $k \sim 10^{-4} \sim 1\text{Mpc}^{-1}$. For small scales, $k > 1\text{Mpc}^{-1}$, the limits are mainly from the research on the primordial black holes (PBHs).⁸ However, the constraints from the PBHs are about 7 orders weaker ($\mathcal{P}_{\mathcal{R}}(k) \sim 10^{-2}$)

^aIn this paper, we use the curvature perturbations ($\mathcal{P}_{\mathcal{R}}$) instead of the density perturbations (\mathcal{P}_{δ}). In the picture of the scale invariant, there is a very simple linear relation between of them.³

than that from the CMB ($\mathcal{P}_{\mathcal{R}}(k) \sim 10^{-9}$). Recently, one new kind of dark matter structures named ultracompact dark matter minihalos (UCMHs) was proposed and they could be used to constrain the PPS of small-scales.⁹ Up to date most of works focus on the dark matter annihilation in the UCMHs. Although the present of dark matter particles has been confirmed, the nature of them are still unknown. There are many theories of dark matter particles and the frequently researched one is the weakly interacting massive particles (WIMPs). According to the theory, WIMPs can annihilate into standard model particles such as photons, electrons, positrons and so on.^{10,11} Due to the basic quality of UCMHs, the annihilation rate of dark matter particles within them is very strong and these objects are the potential high energy astrophysical sources.¹² By the research on the gamma-ray flux from the UCMHs due to the dark matter annihilation one can get the constraints on the cosmological abundance of them.^{3,13} Further, because the formation of UCMHs is related to the primordial density perturbations of small scales, so the limits on their abundance can be converted to the limits on the PPS of small scales. In the Refs. 3, 13, the authors studied the gamma-ray flux from the UCMHs due to the dark matter annihilation and got the constraints on the PPS through comparing with the Fermi observations. They found that the strongest limit is about 5 orders stronger than that of PBHs. In addition to the gamma-ray flux, according to the dark matter theory, the neutrinos are usually produced going with the gamma-ray photons during the dark matter annihilation especially for the lepton channels. In the Ref. 14, we studied the neutrino flux from the UCMHs due to the dark matter annihilation and investigated the limits on the PPS of small scales. We found that the strongest limit is about 5 orders stronger than that of PBHs.

Beside annihilation, in some models dark matter particles are unstable and can decay into the standard model particles. This case is also very interesting in the indirect detection of dark matter.^{15–17} In previous work, we studied the gamma-ray flux from the UCMHs due to the dark matter decay and got the 2σ upper limits on the PPS.¹ Because the decay rate is in proportion to the number density, so the constraints on the PPS are weaker than the annihilation case, but they are still about 4 orders stronger than the cases of PBHs. Recently, the high energy neutrino events are observed by the IceCube and dark matter decay is attracted much more interesting.^{18,19} In the Ref. 20, the authors studied the neutrino flux from the UCMHs due to the gravitino decay. In this paper, we extend the analysis of that work and get the constraints on the PPS of small scales.

This paper is organized as follows. In Sec.2, the main characters of UCMHs are introduced. In Sec.3I, the neutrino flux from UCMHs due to dark matter decay are calculated, the constraints on the mass fraction of UCMHs are given in Sec. 4. In Sec. 5, we get the limits on the PPS of primordial density perturbations. Finally, the conclusions are shown in Sec. 6.

2. The Density Profile of UCMHs

According to the structure formation theory, the density perturbations in the earlier epoch with the amplitude $\delta\rho/\rho \sim 10^{-5}$ can form the present cosmic structures. But if the amplitude of the density perturbations is larger than 0.3(or 0.7) then the primordial black holes (PBHs) are formed.²¹ Recently, Ricotti and Gould proposed that if the density perturbations in early epoch were between $0.003 < \delta\rho/\rho < 0.3$ one new kind of dark matter structures named ultracompact dark matter minihalos (UCMHs) could be formed.⁹ Because the amplitude is not so large, so the formation probability of UCMHs is larger than that of PBHs. After the formation of UCMHs, dark matter particles and baryons are attracted through the radial infall. One dimension simulation indicates that the density profile of UCMHs is in the form as⁹

$$\rho(r, z) = \frac{3f_\chi M_{\text{UCMHs}}(z)}{16\pi R(z)^{\frac{3}{4}} r^{\frac{9}{4}}}, \quad (1)$$

where $M_{\text{UCMHs}}(z)$ is the mass of UCMHs at redshift z , $R(z) = 0.019(\frac{1000}{z+1})(\frac{M_{\text{UCMHs}}(z)}{M_\odot})^{\frac{1}{3}} \text{pc}$ is the radius of UCMHs at redshift z and $f_\chi = \frac{\Omega_{\text{CDM}}}{\Omega_{\text{CDM}} + \Omega_{\text{b}}} = 0.845$.²² From the Eq. (1) it can be seen that the density profile is in proportion to $r^{-2.25}$ and it is steeper than the Navarro-Frenk-White (NFW) profile ($\rho_{\text{NFW}}(r) \sim r^{-1}$ for $r \rightarrow 0$) which has been used usually for the standard dark matter halos.²³ In fact, the center density of UCMHs is not infinitely large and it is usually affected by many effects. The main effect is the angular momentum of dark matter particles during being attracted through the radial infall.³ Following the Ref. 3, we set the minimal radius as

$$r_{\min} = 3 \times 10^{-7} R_{\text{UCMHs}, z=10} \left(\frac{M_{\text{UCMHs}}^0}{M_\odot} \right)^{-0.06}, \quad (2)$$

For the radius $r < r_{\min}$, we assume that the density is constant, $\rho(r)_{r < r_{\min}} = \rho(r_{\min})$. For the other effects which can affect the center density of UCMHs one can refer to the Refs. 3, 24, 25.

3. The Neutrino Flux from UCMHs Due to the Dark Matter Decay

Dark matter as the main component of the Universe has been confirmed by many observations. But the nature of them are still unknown. There are many dark matter models now and some models show that the dark matter particles can decay into standard model particles.¹¹ The productions of dark matter decay can be photons, electrons, positrons or neutrinos.^{15, 26–29} As mentioned in the section 2, because the center density profile of UCMHs is very steep, so the dark matter annihilation rate is very larger in there. In previous works^{3, 12, 13} the authors studied the gamma-ray

flux from the UCMHs due to the dark matter annihilation. They found that the gamma-ray flux would achieve the threshold value of detectors such as EGRET or Fermi. In addition to the gamma-ray flux, according to the dark matter theory the neutrinos are usually produced accompanying the gamma-ray photons especially for the lepton channels. In previous work,¹⁴ we investigated the neutrino flux from the UCMHs due to the dark matter annihilation. We found that the neutrino flux can excess the background neutrino flux which are mainly from the interaction between the cosmic ray and atoms in the atmosphere. Although the dark matter annihilation in the UMCHs is very interesting, if the dark matter particles are not annihilated the decay is another very important issue. So in this paper, we consider the neutrino flux from the UCMHs due to dark matter decay. We consider two popular dark matter models, the weakly interacting massive particles (WIMPs) and the gravitino. The gravitino is the lightest supersymmetric particle and they can decay into standard model particles in the presence of R-parity breaking.³⁰ The decay channels considered here are W^+W^- , $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$ for the WIMPs. For the gravitino decay, there are mainly two-body and three-body decay channels. In this work, we mainly consider the three-body decay channel which has been used to explain the positrons excess.³¹ We use the public code DarkSUSY³² to calculate the energy spectrum of neutrino for the WIMPs decay. For the gravitino decay, we use the forms given in the Ref. 33.

For the neutrino (ν_μ) detection, the main way is to detect the muons (μ) which are produced through the charged current interaction of neutrinos with the medium during propagation. There are two typical types of signal events. One is the upward events that the muons are produced out of the detection and another is the contained events that the muons are produced in the detection. In previous work, we considered these two cases for dark matter annihilation and found that the final limits on the PPS are better for upward events.¹⁴ So in this work, we consider this case. The muon flux for upward events can be written as^{34,35}

$$\frac{d\phi_\mu}{dE_\mu} = \int_{E_\mu}^{m_\chi} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{N_A \rho}{2} \left(\frac{d\sigma_\nu^P(E_\nu, E_\mu)}{dE_\mu} + (p \rightarrow n) \right) \times R(E_\mu) + (\nu \rightarrow \bar{\nu}), \quad (3)$$

where $R(E_\mu)$ is the range which muons can propagate in matter until their energy is below the threshold of the detector E_μ^{th} and it is in the form of $R(E_\mu) = \frac{1}{\beta\rho} \ln\left(\frac{\alpha+\beta E_\mu}{\alpha+\beta E_\mu^{th}}\right)$,³⁶ where $\alpha = 2.0 \times 10^{-6} \text{TeVcm}^2\text{g}^{-1}$ corresponds to the ionization energy loss and $\beta = 4.2 \times 10^{-6} \text{cm}^2\text{g}^{-1}$ accounts for the bremsstrahlung pair production and photonuclear interactions. $N_A = 6.022 \times 10^{23}$ is Avogadro's number. ρ is the density of medium and it is 0.918gcm^{-3} for ice. $d\sigma_{\nu,\bar{\nu}}^{p,n}/dE_\mu$ are the weak scattering charged-current cross sections for neutrino and antineutrino scattered off protons and neutrons.³⁷ $d\phi_\nu/dE_\nu$ is the differential flux of neutrinos from UCMHs due to dark matter decay,

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{m_\chi d^2} \frac{dN_\nu}{dE_\nu} \left(\int_0^{r_{\min}} + \int_{r_{\min}}^{R_{\text{UCMH}}} \right) \rho(r) r^2 dr, \quad (4)$$

where dN_ν/dE_ν is the energy spectrum of neutrino, m_χ and Γ are the dark matter mass and decay rate, d is the distance of UCMHs from the Earth.

The main background of neutrino detection is the atmosphere neutrinos (ATM) which are produced through the interaction between the cosmic ray and the atoms in the atmosphere. These neutrinos has been observed by the detectors such as IceCube.³⁸ The flux of ATM can be written as (in units of $\text{Gev}^{-1}\text{km}^{-2}\text{yr}^{-1}\text{sr}^{-1}$)³³

$$\left(\frac{d\phi_\nu}{dE_\nu d\Omega} \right)_{\text{ATM}} = N_0 E_\nu^{-\gamma-1} \times \left(\frac{a \ln(1+bE_\nu)}{1+bE_\nu} + \frac{c \ln(1+eE_\nu)}{1+eE_\nu} \right), \quad (5)$$

where $a = 0.018$, $b = 0.024$, $c = 0.0069$, $e = 0.00139$, $\gamma = 1.74$ and $N_0 = 1.95(1.35) \times 10^{17}$ for $\nu(\bar{\nu})$. In this work, we set the dark matter mass as $m_\chi = 1\text{TeV}$ and 10TeV . Another important parameter is the decay rate and it has been constrained by many observations.^{39–41} In this work, we set the decay rate as $\Gamma = 10^{-26}\text{s}^{-1}$ and the final results can be applied easily for other values.

4. The Limits on the Mass Fraction of UCMHs

After formation of the UCMHs, one of the important questions is the mass fraction of them in the Universe. In Refs. 3, 13, by researching the gamma-ray flux from the UCMHs due to the dark matter annihilation, the authors found the 2σ upper limit on the fraction of UCMHs is $f_{\text{UCMHs,Anni},\gamma} \sim 10^{-7}$. We studied the gamma-ray flux for the dark matter decay.¹ Because the decay rate is in proportion to the number density of dark matter particles, so the limit is weaker than annihilation case, $f_{\text{UCMHs,Dec},\gamma} \sim 10^{-5}$ (2σ upper limit). In the Ref. 20, the authors researched the neutrino flux from UCMHs due to the gravitino decay and found that the 2σ upper limit is $f_{\text{UCMHs,Dec},\nu} \sim 10^{-3}$. Although the limit is weak, if the dark matter particles are not annihilated the decay is very important.

Following the Ref. 3, the fraction of UCMHs for non-observation of neutrino signals from UCMHs due to dark matter decay can be written as ^b

$$f_{\text{UCMHs}} = \frac{f_\chi M_{\text{UCMH}}}{M_{\text{MW}}} \frac{\log(1-y/x)}{\log(1-M_{d<d_{\text{obs}}}/M_{\text{MW}})}, \quad (6)$$

where y and x are the confidence level corresponding to f_{UCMHs} and detector, respectively. Because for neutrino detection the ATM is the main background, so in

^bMore general form can be found in the Ref. 42(eq.(A2)). The difference of final results deduced by these two forms can be neglected safely for this work.

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this work we set the ATM as the non-detection upper limits. We times the number of ATM with 1.8 as the 5σ upper limits ($\sigma_{\text{total,ATM}} = 16\%^{43}$). $M_{r< d, \text{MW}}$ is the mass of dark matter halo within the radius $r < d$.

Following previous works,^{14, 20} we calculate the neutrino number from a UCMH due to dark matter decay with some confidence level (e.g. 2σ) for some exposure times (e.g. 10 years) using the formula⁴⁴

$$T_{\text{obs}} = \sigma^2 \frac{N_{\text{ATM}} + N_{\text{UCMHs}}}{N_{\text{UCMHs}}^2}, \quad (7)$$

where T_{obs} is the exposure time, N_{UCMHs} is the neutrino number from a UCMH due to dark matter decay and it can be obtained by the integration

$$N_{\text{UCMHs}} = \int_{E_{\mu}^{\text{th}}}^{E_{\text{max}}} \frac{d\phi_{\mu}}{dE_{\mu}} A_{\text{eff}}(E_{\mu}, \theta) dE_{\mu}, \quad (8)$$

where A_{eff} is the effective area of detection, it is a function of energy and zenith angle.⁴⁵ For a fixed exposure time, e.g. 10 years, the distance of UCMH can be obtained from the Eq. 4. Then the upper limits on the mass fraction of UCMHs for 2σ confidence level can be obtained using the Eq. 6. The results are given in Fig. 1 where different decay channels mentioned in previous section are shown. From these plots it can be found that for dark matter decay, the strongest limit on the fraction of UCMHs is from the lepton channels and large dark matter mass, the strongest 2σ upper limit is $f_{\text{UCMHs, Dec., } \nu} \sim 4 \times 10^{-4}$ for gravitino decay with UCMH mass $M_{\text{UCMHs}} \sim 10^7 M_{\odot}$.

In the Ref. 20, the authors also studied the limits on the mass fraction of UCMHs for gravitino decay. The processes of calculations in that paper are slightly different from this work. For example, for the effect area of detector A_{eff} , they assumed a constant value $A_{\text{eff}} = 1 \text{ km}^2$. In this work, we used a general form which depends on the energy and zenith angel. More over, for the definition of mass fraction of UCMHs they used a simple one following the Ref. 13. So the final limits on the mass fraction of UCMHs are different from that of this work for the same decay channel and dark matter mass.

5. Constraints on the Primordial Power Spectrum

As mentioned in above section many inflation models predict that the PPS is scale invariant over a wide scale ranges and some other models show that the PPS is scale dependent.^{46, 47} Therefore, the limits on the PPS is very important for checking different inflation models. The main limits at present focus on the large scales which are mainly from the observations on the CMB, Large-scale structures and Lyman- α forest. For small scales, the main limits are from the research on PBHs^c, but these constraints are very weak. The research on UCMHs provides another better way to

^cThe study on the dissipation of acoustic waves can also be used to constrain the PPS⁴⁸

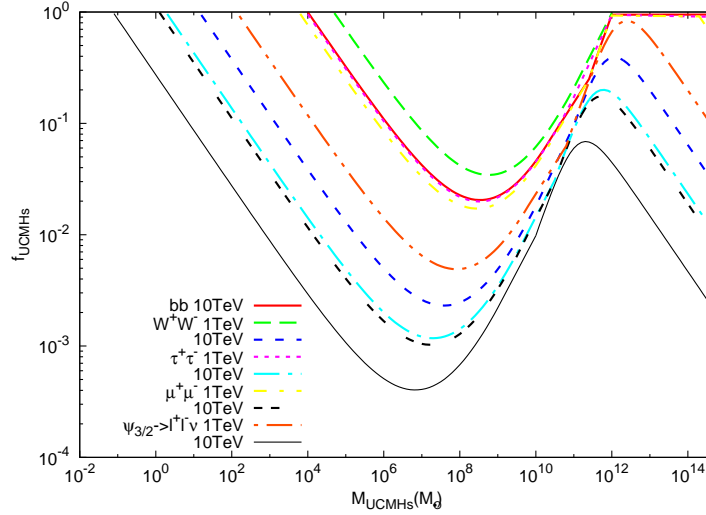


Fig. 1. The 2σ upper limits on the mass fraction of the UCMHs for different decay channels, $\chi \rightarrow W^+W^-$, $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$ and $\psi_{3/2} \rightarrow l^+l^-\nu$ for $l = \mu$. The dark matter mass is 1TeV and 10TeV, the decay rate is $\Gamma = 10^{-26} s^{-1}$, the exposure time of detector is 10 years.

study the PPS of small scales. More detailed calculations of limits on the PPS are given in Ref. 3 and in this paper we only give the main points.

If the initial perturbations are Gaussian the present mass fraction of UCMHs can be written as³

$$\Omega_{\text{UCMHs}} = \frac{\Omega_{\text{DM}}}{\sqrt{2\pi}\sigma_H(R)} \frac{M_{\text{UCMHs},z=0}}{M_{\text{UCMHs},z_{\text{eq}}}} \times \int_{\sigma_{\min}}^{\sigma_{\max}} \exp\left(-\frac{\sigma_H^2(R)}{2\sigma_H^2(R)}\right) d\sigma_H(R), \quad (9)$$

where σ_{\max} and σ_{\min} are the maximal and minimal values of density perturbations required for the formation of UCMHs. These values are the function of redshift. Following the Ref. 3 we use the values corresponding to the redshift, $z = 1000$, at which the UCMHs are formed. The PPS ($\mathcal{P}_{\mathcal{R}}$) is related to the $\sigma_H(R)$ as

$$\sigma_H^2(R) = \frac{1}{9} \int_0^\infty x^3 W^2(x) \mathcal{P}_{\mathcal{R}}(x/R) T^2(x/\sqrt{3}) dx, \quad (10)$$

where $W(x) = 3x^{-3}(\sin x - x \cos x)$ is the Fourier transform of the top-hat windows function with $x \equiv kR$. T is the transfer function of the evolution of perturbations. For more detailed discussions one can see the appendixes in Refs. 3,49.

The constraints on the PPS are plotted in the Fig. 2. From these plots it can be seen that the strongest 2σ upper limit is $\mathcal{P}_{\mathcal{R}} \sim 3 \times 10^{-7}$ for $k \sim 5 \times 10^3 \text{Mpc}^{-1}$. This

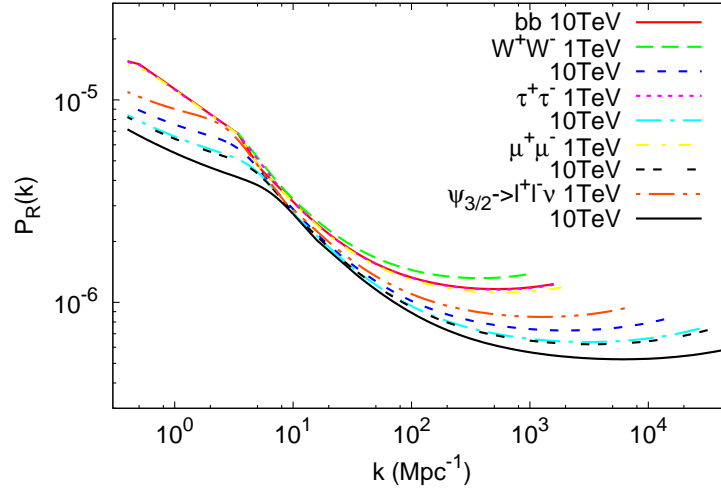


Fig. 2. The 2σ upper limits on the primordial power spectrum of small scales for different decay channels and dark matter mass. The related values of parameters are the same as the Fig. 1.

limit is comparable with the results of Ref. 3. In that work, the authors investigated the gamma-ray flux from UCMHs due to the dark matter annihilation and got the limits on the PPS for the $b\bar{b}$ channel and for the dark matter mass $m_\chi = 1\text{TeV}$. But in this work, one can find that the limits for the $b\bar{b}$ channel are weaker than the lepton channels.

For these results one should notice that they depend on the character of dark matter particles and other aspects such as the density profile of dark matter halo of Milky Way. In previous paper,¹ we researched the dependence of the constraints on the different density profiles of dark matter halo and dark matter decay rate. From that results one can conclude that the constraints are stronger for the NFW density profile or the large decay rate. Another important factor is the dark matter particle mass. From the results of this work and the Refs. 1,14 it can be seen that the limits on the PPS are stronger for the larger dark matter mass.

6. Conclusions

The research on the PPS is very important for checking different inflation models. At present, the main constraints on the PPS focus on the large scales. For small scales the main limits are from the study on the PBHs. Because the formation of UCMHs is related to the PPS of small scales, so the constraints on the mass fraction of UCMHs can be converted to the limits on the PPS. In this work, we considered the neutrino flux from the UCMHs due to the dark matter decay. We found that the 2σ upper limit is $f_{\text{UCMHs}} \sim 4 \times 10^{-4}$ for $M_{\text{UCMHs}} \sim 10^7 M_\odot$. For the limits on the PPS of small scales, the limits are $\mathcal{P}_R \lesssim 3 \times 10^{-7}$ for $k \sim 5 \times 10^3 \text{Mpc}^{-1}$ with

2σ confidence level. These constraints are comparable with that of Ref. 3, 14, but the corresponding scales are different.

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